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THE LAG OF THE HUMIDITY SENSOR IN THE BRITISH RADIO- SONDE

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Summary. Glückauf's laboratory measurements of the behaviour of gold-beater's skin as a function of temperature and relative humidity are summarized. A similar behaviour of the humidity sensor of this material in the British radiosonde is shown by an analysis of some soundings. The response of the sensor in the lower troposphere is satisfactory, and even in the low temperatures of the high troposphere is better than is sometimes thought: in particular, the recordings may show saturation with respect to ice even without correction for lag. It is recommended that the relative humidity indicated there should be corrected for lag, and that values should be reported up to the tropopause, and not, as in present practice, to the -40°C level.

Introduction. In the study of atmospheric soundings it is often desired to establish the presence and height of layers of cloud. Although these should be revealed by the reported relative humidity, it is well known that the sluggishness of the sensors used makes this an unreliable indicator, especially at low temperatures. Nevertheless, since the development of an improved sensor sufficiently inexpensive for routine use still cannot be foreseen, it is useful to have some estimate of the performance of those now employed, and we here review that of the gold-beater's skin in the British radiosonde, particularly to assess whether it can be expected to give a good indication of layers of air nearly saturated with respect to ice, or containing ice clouds, in the high troposphere, where in our latitudes the temperature is about -40°C or less.

The behaviour of gold-beater's skin in the laboratory. Glückauf¹ found that the response of gold-beater's skin to small instantaneous changes of relative humidity in a wind-tunnel could be described satisfactorily in terms of the diffusion of water vapour through a particular boundary-layer configuration. Though a complicated exponential and logarithmic function of time, this response differs little from a simple exponential function of time of the form

$$dh/dt = -(1/T_e) (h - h_e) \quad \dots (1)$$

where h is the relative humidity indicated by the gold-beater's skin
(with respect to saturation over liquid water),
 h_e is the ambient relative humidity,
 t is time

and T_e is the response time of the gold-beater's skin, defined as the time taken for the difference between the indicated relative humidity and a constant ambient value to decrease by the factor $1/e$. T_e is given by Glückauf's theory as a function of the temperature and pressure, and certain skin parameters (Figure 2* and Appendix), and is subsequently called the Glückauf response time T_G .

Two factors which complicate the behaviour of the skin are described by Glückauf:

- (i) T_G is a function of h , being a minimum for relative humidities of about 55 per cent. The continuous line in Figure 1(a) represents an average of a number of curves presented by Glückauf and indicates the magnitude of the variation, though the variation of the response with relative humidity is itself a function of temperature. The response is effectively at its optimum at relative humidities between 30 and 80 per cent.
- (ii) After indicating relative humidities below 30 per cent the gold-beater's skin exhibits hysteresis. If the skin has been calibrated in successively drier atmospheres, subsequently indicated relative humidities below about 70 per cent are too low. Figure 1(b) represents Glückauf's laboratory measurements of this effect at a temperature of 12°C (Glückauf, Figure 3'), Glückauf states that similar curves, in some cases almost identical, have been obtained at temperatures down to -29°C. Figure 1(b) presents the discrepancy in relative humidity as a function of an indicated relative humidity which increases from each of four minimum values. Since the routine calibration of the humidity element of the British radiosonde uses a succession of decreasing standard humidities, it follows that if a minimum relative humidity below 30 per cent is reported subsequent uncorrected values may be too low by as much as 10 per cent.

The effect of hysteresis will be greatest after a sonde has passed through a dry layer sufficiently deep to allow the skin to indicate very low relative humidities. Although this may happen in the middle troposphere, it is probably most frequently associated with low-level subsidence inversions and rather high temperatures which permit rapid response by the hygrometer. The relative humidity (with respect to liquid water) corresponding to saturation with respect to ice is 70 per cent at -36.5°C, and so the skin will rarely recover its calibration if a relative humidity below 30 per cent is reported in the middle troposphere.

It appears appropriate to correct indicated relative humidities first for the effect of hysteresis, which depends only on the state of the skin, and then for lag. A simple correction for hysteresis, which is always an increase of reported humidity, may be found by interpolating between the curves on Figure 1(b).

The gold-beater's skin in the British Mk 2B radiosonde. The exposure of the gold-beater's skin in the wind-tunnel in Glückauf's experiments differed considerably from that in a radiosonde in flight. In the laboratory the plane of the skin was parallel to the airflow, while in the radiosonde it is perpendicular to it and the skin lies downstream of a rain-shield. However,

* Figures 1-7 appear on pages 237-240.

in the radiosonde the response of the skin to a change in relative humidity probably still has an exponential form, and the variation of the response time T_e with temperature in both kinds of exposure is likely to be dominated by that of the saturated water-vapour density with temperature (see Figure 2). Accordingly, the response time of the skin in the radiosonde may be expected to differ from that determined in the laboratory only by a small increase associated with somewhat poorer ventilation.

The original records of some two dozen soundings from Crawley in 1967 were selected and used to estimate values of T_e for the gold-beater's skin from equation (1), introducing the observed values of h and dh/dt and estimates of h_e . Equivalent values at 1000 mb, assuming the pressure dependence to be that of the Gluckauf response time (given in the Appendix), are plotted in Figure 2. In estimating values for T_e in the troposphere, a part of the original record showing a marked change of indicated relative humidity was assumed to have resulted from a discontinuous decrease in the ambient humidity to the value asymptotic to the recorded trend. In this way a maximum value of T_e was obtained.

Because of the greater variability of indicated humidity in the lower troposphere, the time intervals used in the computations were generally shorter there than in the upper troposphere. If, however, gradients of relative humidity had similar magnitudes throughout the troposphere, the effect on the computed lag of assuming these to be infinite (i.e. of assuming a stepped humidity profile) would be greater in the lower troposphere. Since the assumption of discontinuous changes in the ambient humidity can result only in values of T_e which are too large, the tendency to overestimate T_e can be expected to be more noticeable in the lower troposphere.

Some estimates of the response time were made also from the records obtained in the lower stratosphere. The air in the stratosphere was assumed to be completely dry, and T_m , (the maximum value of T_e) computed from equation (1) was then found to have a minimum on each sounding at a level some 50 mb above the tropopause (as shown for example in Figure 7). Such minimum values provided the points shown at the lowest temperatures in Figure 2. Measurements of frost-points from aircraft² show that the average relative humidity 50 mb above the tropopause is less than 4 per cent, so that the assumption of a value of zero should lead to reasonable results, but it is possible that at these levels the air close to the gold-beater's skin is significantly contaminated by the evaporation of water vapour from the balloon or the structure of the radiosonde itself, so that the computed values of T_m may still be too large.

From Figure 2 it appears that the estimated values of T_e and T_m deviate from those of T_G in the manner anticipated. Values obtained from the middle and upper troposphere are in closest agreement with T_G , and suggest that the latter correctly represents the response time of the humidity element of the Mark 2B radiosonde to within a factor of about two. Values of T_e in the troposphere were computed from fifteen soundings, seven of which each provided at least three points on Figure 2. Response times computed at different levels from the same sounding often showed a consistent bias away from the axis of the bulk of the values, which may be due to variations in the characteristics of individual samples of the gold-beater's skin.

Figure 3 displays T_G as a function of height or pressure in the International Civil Aviation Organization (ICAO) atmosphere. The discontinuity in its gradient at the tropopause results from the change in lapse rate there; in the isothermal stratosphere T_G is simply proportional to the square root of the air pressure.

The response of the idealized humidity sensor. The behaviour of the idealized gold-beater's skin is described by Figures 1 and 2. We may consider the response of such a sensor in a radiosonde which rises with the typical speed of 6 m/s using the following four simple models of the vertical profile of the relative humidity in the atmosphere.

(i) A completely dry layer lies above one in which the gold-beater's skin has reached equilibrium under a relative humidity of 60 per cent; the model atmosphere is isothermal.

In Figure 4, curve A shows the response of the gold-beater's skin as a function of the time after the sensor enters the dry layer (the scale of the abscissa is made non-dimensional by dividing the time elapsed by the minimum response time, i.e. T_G at relative humidities of about 50 per cent; T_G varies with indicated relative humidity according to the continuous line in Figure 1(a). For comparison, the curve B represents a purely exponential response, T_G remaining fixed at the minimum value. The increasing difference between the two curves for values of the parameter (time/minimum T_G) greater than unity results from the rapid increase of T_G with decreasing relative humidity when the latter is below 30 per cent (Figure 1(a)).

When the gold-beater's skin is indicating a measurable rate of change of relative humidity, the Glückauf response time T_g defined by Figures 2 and 1(a) can be used in a finite difference form of equation (1) to estimate the true ambient humidity h_t . We have

$$h_t = T_G(h_2 - h_1)/\Delta t + (h_1 + h_2)/2 \quad \dots (2)$$

where h_1 and h_2 are respectively the reported humidities at the beginning and end of the time interval Δt , and the response time T_G is appropriate to the conditions mid-way through the time interval.

Figure 4 contains values of the ambient humidity computed in this way using humidities read from curve A and values of T_G /minimum T_G from Figure 1(a). The scatter in the values is a measure of the accuracy with which the curves can be read, though the value marked E is significantly above zero because the linear relationship of equation (2) is not accurately applicable to the non-linear curve A when the time interval ΔT is greater than T_G . Since intervals between successive observations of relative humidity by the radiosonde may be as large as 30 seconds, correction for lag is justified only at temperatures below about -20°C (above the 500-mb level), when the Glückauf response time is greater than 30 seconds.

From equation (1) it is apparent that if the correction $(h - h_t)$ which is applied to the indicated humidity is in error only because of the value used for the response time, then the fractional error in the correction is just the fractional error in the response time (estimated from Figure 2 as likely to be as much as 0.3).

When the minimum response time is less than about 1.5 minutes, corresponding to temperatures above -33°C , the gold-beater's skin has indicated

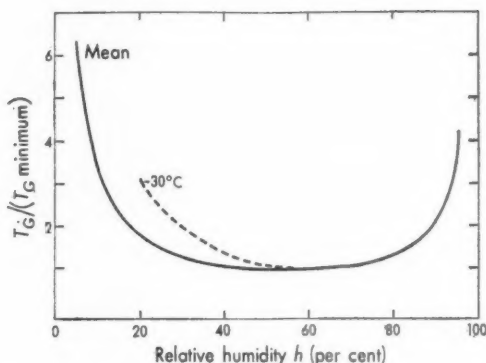


FIGURE 1(a)—VARIATION WITH INDICATED RELATIVE HUMIDITY h OF THE GLÜCKAUF RESPONSE TIME T_G DIVIDED BY THE MINIMUM VALUE AT THE SAME TEMPERATURE

The continuous line represents the mean of Glückauf's observations over a range of temperatures from -30°C to 18°C , and the pecked line represents his observations at -30°C .

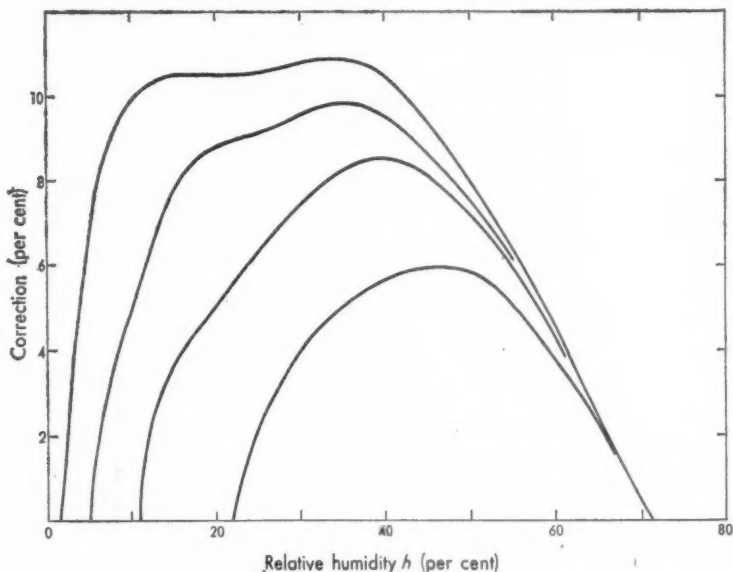


FIGURE 1(b)—THE EFFECTS OF HYSTERESIS ON THE RELATIVE HUMIDITY INDICATED BY GOLD-BEATER'S SKIN IN THE LABORATORY (FIGURE 3¹)

Each curve shows the correction to be applied to any indicated relative humidity after a certain minimum value has been indicated. Corrections needed following the indication of minimum relative humidities other than 1.7, 5, 11 and 22 per cent can be found by interpolation between the curves.

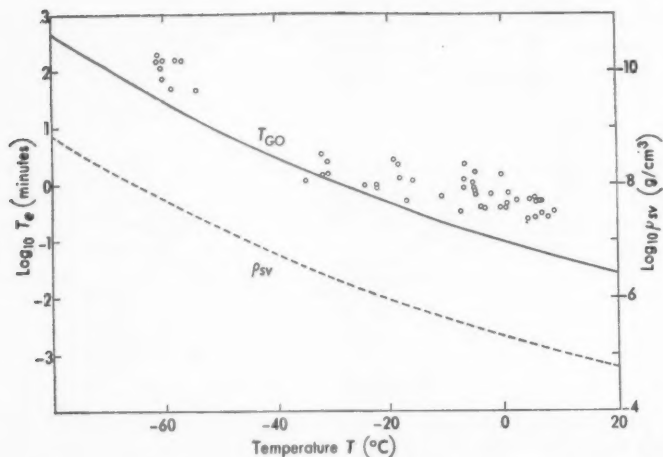


FIGURE 2—VARIATION WITH TEMPERATURE T OF THE GLÜCKAUF RESPONSE TIME (SEE P. 234 AND APPENDIX)

The continuous line is $\log_{10} (T_{GO})$, where T_{GO} is the Glückauf response time at a pressure of 1000 mb and is related to the response time T_G at a pressure of p mb by $T_G = T_{GO}(p/1000)^{1/2}$. Response times T_e computed from radiosonde ascent records were reduced to equivalent values at a pressure of 1000 mb using the same relation. The density of vapour saturated with respect to liquid water, ρ_{sv} , is included for comparison (pecked line).

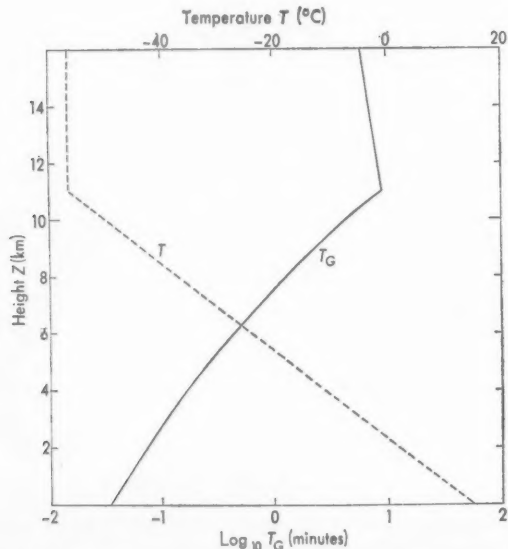


FIGURE 3—THE GLÜCKAUF RESPONSE TIME T_G AND AIR TEMPERATURE T AS A FUNCTION OF HEIGHT Z IN THE ICAO STANDARD ATMOSPHERE

— T_G - - - T

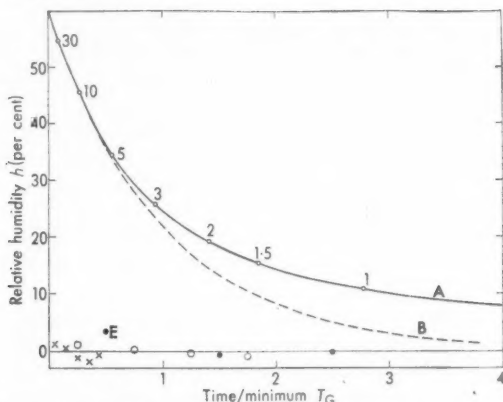


FIGURE 4—THE RESPONSE OF A HUMIDITY SENSOR AFTER ENTERING A COMPLETELY DRY ISOTHERMAL LAYER

The initial indicated relative humidity is assumed to be 60 per cent; the subsequent response is represented by a curve A when the response time varies with indicated relative humidity according to the continuous line on Figure 1(a), and by curve B when the response time is constant. The ordinates at the points on the curve A marked by the numbers N show the relative humidity indicated 1 km above the base of the dry layer by a sensor with a response time of N minutes (the sensor rises at 6 m/s). Ambient relative humidities computed using equation (2), with half-minute time intervals, and curve A, are marked respectively by full circles, open circles and crosses when the response times are 0.5, 1 and 5 minutes.

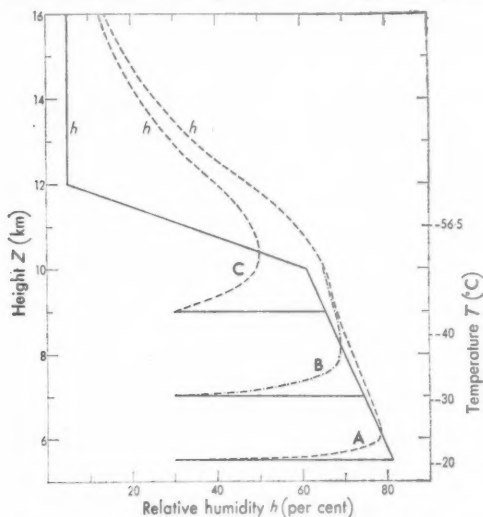


FIGURE 5—THE RESPONSE OF HUMIDITY SENSORS, WITH RESPONSE TIMES DEFINED BY FIGURE 2, DURING AND AFTER PENETRATION OF DAMP LAYERS (SATURATED WITH RESPECT TO ICE) IN THE HIGH TROPOSPHERE OF THE ICAO ATMOSPHERE. Curves A, B and C respectively represent the response when the relative humidity rises from 30 per cent to ice saturation at heights of 5.5, 7 and 9 km, and subsequently falls above 10 km to a constant value of 5 per cent in an isothermal atmosphere as shown by the continuous lines. The rate of change of indicated relative humidity with height (or time) is zero when the sensor indicates the true relative humidity.

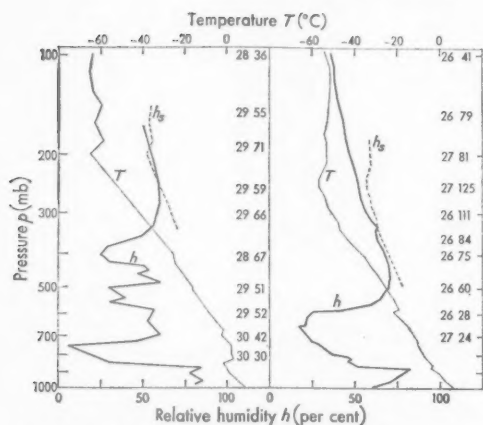


FIGURE 6—THE SOUNDINGS FROM CRAWLEY AT ABOUT 1200 GMT (a) ON THE LEFT, 12 NOVEMBER 1967, AND (b) ON THE RIGHT, 12 MARCH 1967

The profiles of relative humidity h and temperature T , represented respectively by thick and thin continuous lines, were taken from the original record of the ascent. The pecked line is the relative humidity h_s corresponding to ice saturation at the indicated temperatures. The reported winds in tens of degrees and knots are included on the right-hand side of each diagram.

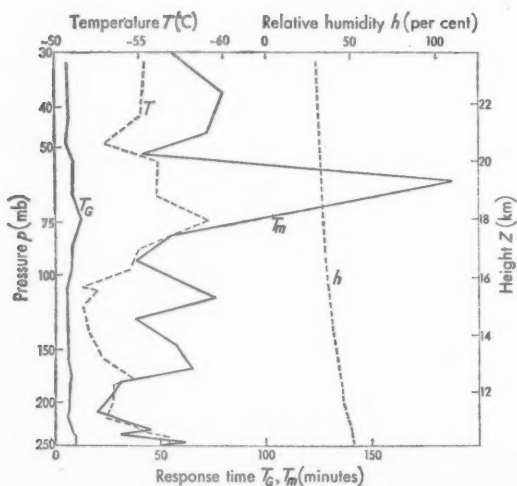


FIGURE 7—SOUNDING THROUGH THE LOWER STRATOSPHERE FROM CRAWLEY AT ABOUT 1200 GMT, 12 MARCH 1967

Temperature T , the Glückauf response time T_G , the maximum response time T_m (the value of T_e satisfying equation (1) when h_e is zero), and the relative humidity h indicated by the sensor are shown as functions of height Z , or of pressure p .

most of the change in the ambient relative humidity after penetrating 1 km into the dry air (that is after about 3 minutes). Because of desiccation, however, the response time at this level has risen to many times the appropriate minimum value and the instrument will very rarely indicate relative humidities as low as 5 per cent, since this would require the existence of a very dry layer many kilometres deep. This is consistent with the experience that radiosondes seldom indicate relative humidities much below 10 per cent in subsided air in the low troposphere, although values as low as 1.5 per cent occur, as shown for example by observations of frost-point from balloons³ and aircraft,⁴ and by inference from the frequently observed radar-ducting in the Caribbean.⁵

When the minimum response time is of order 10 minutes, corresponding to temperatures below -50°C , the idealized gold-beater's skin grossly misrepresents features of the stratification of relative humidity having vertical dimensions of about 1 km, though they may be reconstructed from the indicated values.

(ii) A cloud layer 300 m thick, saturated with respect to liquid water, lies above a layer in which the sensor has reached equilibrium under a relative humidity of 50 per cent. The model atmosphere is isothermal.

The relative humidity indicated by the sensor was computed as a function of time using a form of equation (1), values of T_G appropriate to temperatures of 5°C and -5°C and the indicated relative humidity (the continuous curve on Figure 1(a)). At a temperature of 5°C the sensor indicated a relative humidity of 96 per cent 90 m above the cloud base, while at -5°C 91 per cent was indicated at the same level. In each case the value indicated at the top of the saturated layer exceeded 97 per cent.

This performance seems impressive in view of the common experience that soundings usually fail to find saturated or nearly saturated layers on occasions when altocumulus clouds are reported, although shallow layers with distinct maxima of relative humidity are usually indicated (as shown for example in Figure 6(a) at about 650 and 470 mb, when medium-level cloud $C_M=3$ was reported by most stations in southern England). However, on such occasions the proportion of saturated air at the cloud levels may be smaller than it seems, considering the frequently patchy distribution of cloud, the presence of much thinner cloud or even clear spaces between individual cloud elements, and the effect of perspective in obscuring gaps at low elevations.

(iii) The relative humidity decreases linearly at the rate of 40 per cent per kilometre in an isothermal atmosphere.

The difference between reported and true ambient humidities is given by

$$h - h_s = -w(\partial h_s / \partial z) T_G (1 - \exp(-t/T_G)) + \Delta h_s \exp(-t/T_G) \quad \dots (3)$$

where w is the vertical speed of the sensor,

$\partial h_s / \partial z$ is the vertical gradient of relative humidity and

Δh_s is the initial value of $(h - h_s)$. The value of $(h - h_s)$ approaches the limit $-w(\partial h_s / \partial z) T_G$ with increasing time; the values of this limit are given below for three values of T_G .

Response time T_G in minutes	0.2	1	5
Corresponding temperature in $^{\circ}\text{C}$	-9.5	-29	-45
$-w(\partial h_s / \partial z) T_G$ percentage R.H.	2.9	14.4	72 (54)

When the response time is 5 minutes ($h - h_i$) approaches the limiting values of 72 per cent so slowly that when the ambient relative humidity has reached zero the value of the first term on the right of equation (3) is only 54 per cent. The treatment assumes the response time to be constant, ignoring the larger values associated with extremes of relative humidity.

Thus the comparatively modest response time of 1 minute leads to considerable over-estimation of relative humidity when this has a large negative vertical gradient. The correction for lag, using equation (2) is, of course, still applicable.

(iv) Layers of various thicknesses, saturated with respect to ice, lie in the high troposphere of an ICAO atmosphere, above a layer in which the sensor has reached equilibrium under a relative humidity of 30 per cent with respect to liquid water. The relative humidity decreases linearly with height through a layer 2 km thick centred on the tropopause and remains constant at 5 per cent up to a height of 16 km. This profile is a simple model of conditions commonly observed on the anticyclonic side of polar-front jet streams.

Figure 5 presents the profiles of relative humidity indicated by the idealized gold-beater's skin when rising at 6 m/s and entering the ice-saturated layers at heights of 5.5, 7, and 9 km. The response time is determined by the ambient temperature and pressure, using Figure 2. The effects of desiccation of the sensor are ignored, but from Figures 1(a) and 5 can be seen to be unimportant at heights below 13 km. Equation (3) is used to compute the indicated relative humidity as a function of time and thus of height, since between heights of 5 and 10 km in the ICAO atmosphere the relative humidity with respect to liquid water at saturation with respect to ice is a nearly linear function of height. In all three cases the sensor over-estimated the relative humidity in some regions, especially in the stratosphere. It appears that the vertical gradient of relative humidity associated with ice saturation in the high troposphere, together with the appropriate values of response time, is sufficient to account for the occasional indications of supersaturation with respect to ice found on routine soundings (see, e.g., Figure 6(a)).

When the saturated layer is encountered at a temperature of -20°C (curve A of Figure 5) the height of its lower boundary is over-estimated by 0.6 km, whereas when it is encountered at temperatures of -30°C (curve B) and -40°C (curve C) it is respectively over-estimated by 1.2 km and over 2 km. Evidently it may commonly happen that saturated layers are insufficiently thick for ice saturation to be indicated.

The smooth profiles of humidity indicated in the stratosphere are qualitatively typical of routine soundings and though the magnitudes of the computed gradients are rather too large (see Figure 7) this can be explained, in part at least, by the neglect of the increase in the response time caused by desiccation.

Observed humidity and temperature profiles. Figure 6 contains the humidity and temperature profiles of two soundings from Crawley. At the time of the first, 1200 GMT on 12 November 1967, nearly every station in the British Isles south of a line from the Wash to Malin Head reported high cloud ($C_H = 2$), and most stations in southern England reported middle cloud ($C_M = 3$). The strongest wind at the 300-mb level was observed at

Stornoway (134 kt from 280°); thus Crawley lay well to the south of the axis of the jet stream. The extensive shield of dense cirrus is represented on the midday sounding (Figure 6(a)) by the damp layer above the 350-mb level. The value of 5 per cent for the relative humidity reported at about 750 mb is unusually low.

At the time of the second, 1200 GMT on 12 March 1967, near Crawley the sun was completely obscured by an overcast of altostratus with mamma; there was no lower cloud. The cloud-filled layer, saturated with respect to ice, is clearly indicated on Figure 6(b) and probably had a lower boundary at about 550 mb.

It is confirmed by Figure 6 that deep layers of damp air in the upper troposphere are represented with useful accuracy even by the uncorrected readings of the routine radiosonde. It is therefore unfortunate that the present practice is to cease reporting relative humidity when the temperature falls below -40°C . The synoptic report from the sounding represented by Figure 6(a) therefore omitted humidity data above the 308-mb level, and the very clear evidence of a deep cloud layer in the high troposphere was effectively lost. Because of the smoothing effect of the large lag of the gold-beater's skin, only a few more values would be needed to provide a sufficiently complete record up to the tropopause.

Relative humidities indicated in the lower stratosphere. Using radiosonde observations of humidity and equation (1), maximum values for the response time of the gold-beater's skin (T_m) were computed assuming the ambient humidity to be zero. Five of the routine soundings made from Crawley early in 1967 were chosen because, in each, a marked rise of indicated humidity towards ice saturation in the high troposphere showed that the sensor had not become unresponsive because of excessive desiccation or some other reason. Figure 7 presents the vertical profiles of temperature and humidity from one sounding, together with the profiles of T_m and the Glückauf response time T_G (as defined by Figure 2 and the pecked line on Figure 1(a)).

Although the vertical gradients of humidity indicated in the stratosphere are small, they vary sufficiently in the vertical to produce considerable variations in T_m . Three features of this structure in Figure 7 are common to the five soundings examined.

- (i) There is a decrease of T_m in the first 50 mb above the tropopause, showing that the ambient relative humidity is decreasing upwards and is not yet negligible.
- (ii) A minimum of T_m occurs some 50 mb above the tropopause. In Figure 7 this is 3.1 times the appropriate Glückauf value, and Figure 2 shows that there were similar discrepancies on all the soundings examined. In Figure 7 the observations of humidity at the level of the minimum lag would be consistent with the value of T_G if the true ambient relative humidity were 32 per cent. However, frost-point measurements in the lower stratosphere² show that the average value of relative humidity 50 mb above the tropopause over southern England is about 4 per cent, and although a higher value may be more appropriate to the type of sounding considered here, 32 per cent is probably unrealistically high. It is possible that at these

levels the processes determining the response of the gold-beater's skin differ from those considered by Glückauf, but it seems more probable, particularly since in these instances the radiosondes had previously indicated high relative humidities in the upper troposphere, that the environment of the gold-beater's skin was being contaminated by water vapour escaping from the structure of the sonde. This phenomenon is known to be important with other techniques at low pressures.³

- (iii) At lower pressures T_m increases, though the magnitude and nature of the increase differs considerably from one sounding to another. As in Figure 7, magnitudes and amplitudes of fluctuations of T_m show some correlation with temperature and are much greater than those of the Glückauf response time. Contamination probably occurs but, to explain the maxima of T_m , it would be required to occur preferentially at temperature minima.

The amount of water necessary to contaminate the environment of the gold-beater's skin sufficiently to reduce the average magnitude of T_m to that of the Glückauf response time can be estimated. Depending on whether the cross-section of the airflow being contaminated is about 4 cm², corresponding to the region close to the gold-beater's skin, or is about 10⁴ cm², corresponding to the wake of the balloon, the amounts of water required to saturate the 11-km layer between 180 mb and 30 mb are respectively 6×10^{-2} g and 140 g. Both values seem unrealistically large, and make significant contamination seem doubtful, but no other explanation of the observed behaviour can be suggested.

Conclusion. The humidity sensor of gold-beater's skin on the British radiosonde has a satisfactory response at the temperatures typical of the lower troposphere, and the indicated values can mostly be accepted without correction for lag as appropriate to the layers a few hundred metres or more deep which are effectively sampled by the technique adopted for routine soundings. However, a substantial increase in the response time as the indicated relative humidity decreases below 10 per cent or increases above 90 per cent (with respect to liquid water) hinders the recording of such extremes.

The response time of the sensor increases with decreasing temperature; it exceeds 1 minute at temperatures below about -30°C and 15 minutes at temperatures below about -60°C. The accurately recorded trend of the indicated value offers the possibility of making corrections to obtain true relative humidities in the upper troposphere, although the correction is complicated by the uncertain effects of hysteresis after exposure to very low humidities in the lower troposphere and, perhaps, of variations in the characteristics of individual sensors, apart from some doubt about the effect of the exposure and ventilation in the radiosonde, which differ from those in the one series of laboratory studies which have been made. Nevertheless two examples of soundings are given in which the sensor responded well in ice clouds in the high troposphere, even after previously passing through layers of very low relative humidity. In layers of ice cloud the relative humidity probably hardly ever exceeds that corresponding to saturation with respect to ice, at which the relative humidity with respect to liquid water (to which the sensor responds) is usually between about 50 and 80 per cent, where the sensor

has its best performance. The present arbitrary practice is to cease reporting the relative humidity at air temperatures below -40°C , and to make no corrections for lag or hysteresis. This practice might well be reviewed and humidities reported at levels up to the tropopause, particularly when soundings are evaluated by computer rather than by hand, since it sometimes fails to indicate the presence of saturated layers in the high troposphere, which are important in some kinds of investigation.

In the stratosphere the trend of the indicated relative humidity is generally still measurable, but an analysis suggests that it cannot usefully be corrected, because of irregular behaviour which can probably be attributed to a significant contamination of the air near the sensor with water vapour derived from the balloon train.

Appendix

The theoretical lag coefficient. On the assumption that the interchange of water vapour between gold-beater's skin and the atmosphere is determined by diffusion through a turbulent boundary layer, Glückauf¹ derives a relationship

$$(h - h_e)/(h_0 - h_e) = F(kt/\sqrt{l}) \quad \dots (4)$$

- when F is a complicated exponential and logarithmic function,
 h is the relative humidity reported by the gold-beater's skin,
 h_e is the steady ambient relative humidity which changed instantaneously from h_0 at zero time t ,
 l is the length of skin along the airflow,
 and k is a parameter whose dependence on pressure and temperature is described by Glückauf's theory.

Equation (4) agrees very closely with measurements made in a wind-tunnel by Glückauf, but, as is apparent in the following table, differs considerably from the simple exponential relationship

$$(h - h_e)/(h_0 - h_e) = \exp - 2(kt/\sqrt{l}) \quad \dots (5)$$

only for values of $X = (kt/\sqrt{l})$ greater than 1, i.e. when the gold-beater's skin has practically reached equilibrium with the changed environment.

X	$F(X)$	$[\exp(-2X)]/F(X)$
0.1	0.725	1.13
0.2	0.579	1.16
0.4	0.390	1.15
0.8	0.199	1.01
1.6	0.063	0.65

Thus the response of the gold-beater's skin is effectively exponential in time and has a definite response time T_G , where T_G is $\sqrt{l/2k}$.

Glückauf derives an expression for k in which T_G in seconds is given by

$$T_G = 1.125(aA_0/D\rho_s)(\nu/u)^{\frac{1}{2}}$$

where A_0 is the mass per unit area of the gold-beater's skin, which averaged $1.07 \times 10^{-3} \text{ g/cm}^2$ in a sample of 2000 cm^2 supplied by the Meteorological Office.

a is defined by $dA/dh = aA_0$, relating the fractional change in weight per unit area of skin to a change in relative humidity. Glückauf's value of 2×10^{-3} is taken to be correct. Note that this represents the maximum sensitivity of the skin at

- intermediate relative humidities; at larger and smaller relative humidities a is larger, giving a greater response time.
- D is the diffusivity of water vapour in air; it may be written as $D_0(T)(1000/p)$, where $D_0(T)$ is the diffusivity at 1000 mb and is a function of temperature T only.⁶
- ρ_s is the density of water vapour saturated with respect to liquid water at the air temperature and is effectively a function of temperature only.^{6,7}
- ν is the kinematic viscosity of air and may be written as $\nu_0(T)(1000/p)$, where $\nu_0(T)$ is a function of temperature only (Smithsonian Tables, p. 394).
- u is the ventilation speed of the gold-beater's skin, which is arbitrarily assumed to be 300 cm/s, half the average vertical speed of a radiosonde, to allow for obstruction of the airflow near the skin by the rain shield.
- l is the length of the gold-beater's skin in the direction of flow and is taken to be 1.5 cm, though in fact the skin in the Mark 2B radiosonde is exposed with its surfaces perpendicular to the incident airflow.

The expression for the Glückauf response time is then

$$T_G = T_{GO}(T) (p/1000)^{\frac{1}{2}} \quad \dots (6)$$

and from numerical values of the above parameters T_{GO} has been computed to be the function of temperature represented by the continuous line on Figure 2.

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551.577-36:551.577-37(424)

ESTIMATES OF THE DURATION OF SHORT-PERIOD RAINFALL RATES BASED ON CLOCK-HOUR VALUES

By J. BRIGGS and J. A. HARKER

Summary. Data were examined from special recording gauges in operation at Winchcombe during moderate or heavy rain (mainly showery type), and a distribution was obtained of the two-minute rainfall intensities associated with various ranges of clock-hour totals. A graph was then produced to show the percentage of two-minute intensities which equalled or exceeded various multiples of the clock-hour rainfall. This graph (or conversion factors obtained from it) can be used to obtain estimates from clock-hour data of the number of hours per year with rainfall intensities equalling or exceeding specified values, and examples are given to show how these estimates compare with estimates made by other methods.

Introduction. Estimates of the probability of instantaneous rainfall rates exceeding certain critical values are of importance for a number of design problems. Unfortunately there is little direct evidence available from short-period measurements of rainfall, and so to meet the questions posed by designers it is necessary to calculate the chances of short-period rainfall of high intensity from data more commonly to hand. For many stations there are now several years of 'clock-hour' rainfall totals and these are often used to produce tabulations of the occurrences of specified rainfall rates. The 'clock-hour' total is simply the amount of rain to fall in a given clock-hour; the rain may have accumulated fairly evenly throughout the hour but, at the other extreme, it may have fallen in one minute or less. In general the clock-hour total will include a variety of instantaneous rates but, over a large sample, it may be possible to determine the average distribution of instantaneous rates about the clock-hour total, and so to derive factors which can be used to estimate the probabilities of short-period rain intensities from the available clock-hour statistics. An analysis of this kind was made by H. E. Bussey¹ and he obtained figures for the duration of one-minute rates of rainfall for the vicinity of Washington.

Distribution of two-minute falls for specified ranges of clock-hour rainfall. Bussey's figures do not examine the variation of the distribution of short-period rates about the clock-hour total as this clock-hour total is varied. It seemed desirable to examine this variation and, at the same time, to provide data for this country which might be compared with Bussey's figures. An opportunity to do this was provided by the results of Meteorological Office experiments with a network of recording rain-gauges at Winchcombe. These experiments were similar to those at Cardington which have been described by Holland.² In the Winchcombe experiments the rain-gauges were sited in a small valley in the Cotswolds. Up to 24 rain-gauges were in use at one time and individual gauge totals were recorded at intervals of two minutes. The experiments were mostly in the months of March to October and were limited to the years 1962 to 1967. Analysis was restricted to those occasions in which the maximum two-minute fall in any gauge of the network was 0.5 mm or more. This restriction essentially limited the analysis to occasions of moderate or heavy rain and so basically to showery type rain, though the location of the network was such that orographic effects tended to intensify frontal rains and some frontal rainfall was included in the analysis.

From the recorded Winchcombe data all occasions were next selected when any particular gauge was working throughout any given clock-hour and the distribution of two-minute falls was noted for that gauge and hour. The results were then sorted according to the clock-hour value so that any systematic variation of the distribution with change of clock-hour value would show up. Table I presents the results of this sorting.

Table I shows that 2748 clock-hours were included in this analysis. Many of these represented multiple observations of a particular shower but, since the effect of any shower varied considerably across the network, depending on the location of each gauge in relation to the shower, it is considered that the best representation of average distributions will be obtained by using

TABLE I—NUMBER OF OCCASIONS OF TWO-MINUTE RAINFALL AT GIVEN INTENSITIES FOR SPECIFIED RANGES OF CLOCK-HOUR RAINFALL

Clock-hour rainfall mm	Two-minute rainfall (mm)						≥ 100	Number of two-minute occasions*		
	<0.3	0.3-0.9	1.2-5.1	5.4-9.9	10.2-24.9	25.2-50.1				
<5	25 413	15 669	20 663	4 131	2 294	395	14	1	0	68 550 (2 285)
5-9.99	1 824	1 377	4 098	2 286	1 796	506	75	8	0	11 970 (399)
10-14.99	329	91	290	221	293	177	55	12	2	1 470 (49)
15-19.99	47	8	82	103	60	48	29	8	5	390 (13)
20-24.99	9	4	14	3	11	9	8	2	0	60 (2)
									Total	82 440 (2 748)

*Figures in brackets are equivalent clock-hours

all the gauge values. Two-minute rain totals were not read to better than 0.01 mm; this accounts for the column headings of Table I, i.e. to the nearest 0.3 mm/h.

Table I was next used to obtain Figure 1, which shows the percentage of two-minute intensities which exceeded various multiples of the clock-hour intensity, R , shown as ordinates on the figure. The different ranges of R of Table I are represented by separate curves on Figure 1. Inspection of the figure reveals close agreement between the distributions associated

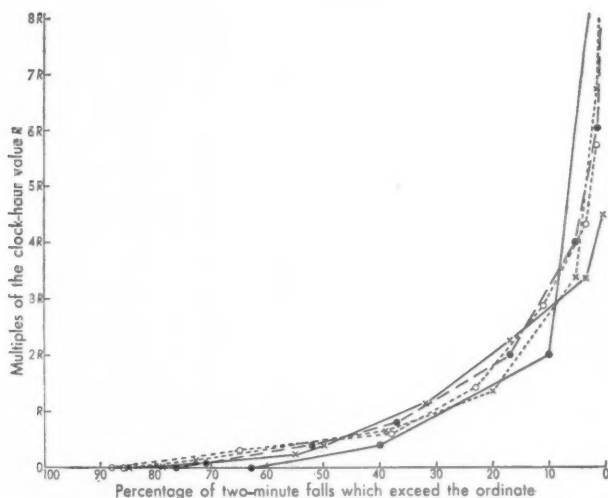


FIGURE 1—DISTRIBUTION OF TWO-MINUTE FALLS ABOUT THE CLOCK-HOUR VALUE

- | | | | |
|-----------|------------------------------|-----------|------------------------------|
| — | R in range < 5 mm/h | x - - - x | R in range $5-9.99$ mm/h |
| - . - . | R in range $10-14.99$ mm/h | o - - - o | R in range $15-19.99$ mm/h |
| x - - - x | R in range $20-24.99$ mm/h | | |

with the different clock-hour ranges, but two minor discrepancies require some comment. Firstly, the lowest range of R has a considerably higher percentage of short-period falls shown as trace or no rainfall than have the other ranges. This is an effect of the detection limit of the rain-gauges, for with a low value of R a relatively high fraction of R is needed to ensure detection. Secondly, the curve corresponding to the highest range of R has a somewhat lower percentage of short-period falls at high multiples of R than have the other ranges. In this instance it must be noted that the sample is limited to only two clock-hours and this can hardly provide an adequate selection of the high multiples of R .

The original selection of data introduced a bias towards showery-type rain, since rains in which a rate of 15 mm/h was not reached by at least one gauge in any two-minute period were excluded. Nevertheless, Table I shows that by far the highest number of clock-hour totals, 2285, corresponded to intensities of below 5 mm/h. Bearing in mind the two discrepancies already discussed, it is thought that the curves of Figure 1 are sufficiently close to

permit the substitution of an average curve as representative of the distribution of short-period means about the clock-hour total for all ranges of that total. Moreover, it is thought that the bias against frontal rains will not introduce any serious errors when this average distribution is used to assess durations of high-intensity short-period rains.

Figure 2 presents the average curve based on Figure 1. In reaching this average there is a self-contained check which has been used. Over a long period the average curve must show the relative distribution of short-period rainfall rates for the average clock-hour with rainfall amount R . Thus the

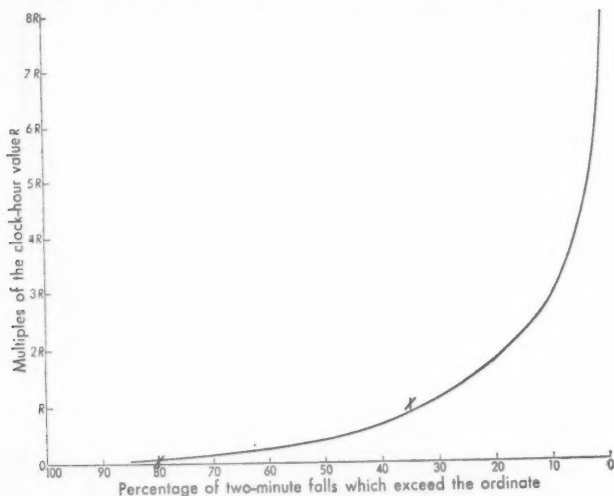


FIGURE 2—AVERAGE DISTRIBUTION OF TWO-MINUTE FALLS ABOUT THE CLOCK-HOUR VALUE (R)
 X = Bussey value

abscissa corresponding to a given ordinate of Figure 2 must indicate the percentage of the average clock-hour for which the short-period rate exceeds the value of the ordinate. Thence the total area under the curve of Figure 2 is a measure of the amount of rain to fall in the average hour, but this amount is R , and so the area under the curve must equal that below the ordinate R taken over the whole hour (100 per cent of the time). Also shown on Figure 2 are crosses representing two values quoted by Bussey, namely that about 20 per cent of each hour corresponded to 'trace' or 'zero' rain and that rainfall exceeded R for about 35 per cent of each hour. Bussey also noted that values of $5R$ to $6R$ were exceeded fairly commonly for a few minutes each hour. It is difficult to represent this last statement adequately on the figure, but it is quite clear that there is very good agreement between the Winchcombe and Washington average distributions, and this suggests that Figure 2 may be generally applicable except possibly for light frontal-type rains.

Estimates of two-minute intensities from clock-hour data. If clock-hour data are available for any particular station for a sufficiently long period, then Figure 2 can be used to give estimates of the percentages of the two-minute falls which occurred with intensities at or above specified values.

In practice it is more convenient to use the figure to produce conversion factors which can be applied directly to the clock-hour totals. Table II presents these factors as percentages.

TABLE II—PERCENTAGES OF THE CLOCK-HOUR DURING WHICH THE TWO-MINUTE RAINFALL INTENSITY EQUALS OR EXCEEDS SPECIFIED VALUES. PERCENTAGES ARE GIVEN FOR A SELECTION OF CLOCK-HOUR TOTALS

Clock-hour total (mm)	Intensity (mm/h)								
	0.1	1	5	10	20 percentages	25	50	75	100
0.1	32	0	0	0	0	0	0	0	0
1	80	32	02	0	0	0	0	0	0
2	85	45	12	02	0	0	0	0	0
3	85	53	21	08	01	0	0	0	0
4	85	60	27	12	02	01	0	0	0
5	85	65	32	17	05	02	0	0	0
6	85	70	35	21	08	04	0	0	0
7	85	75	38	24	10	06	01	0	0
8	85	77	41	27	12	08	01	0	0
9	85	79	43	30	14	10	02	0	0
10	85	80	45	32	17	12	02	0	0
11	85	81	47	34	19	14	03	01	0
12	85	82	49	35	21	16	04	01	0
13	85	82	51	37	22	18	05	01	0
14	85	82	52	39	24	19	07	02	0
15	85	83	53	40	26	21	08	02	0
16	85	83	54	41	27	22	08	03	01
17	85	84	56	42	28	24	09	04	01
18	85	84	57	43	30	25	10	04	02
19	85	84	59	44	31	26	11	05	02
20	85	85	60	45	32	27	12	06	02
21	85	85	61	46	33	28	13	07	03
22	85	85	62	47	34	29	14	08	03
23	85	85	63	48	35	30	15	08	04
24	85	85	64	49	36	31	16	09	04
25	85	85	65	50	36	32	17	09	05
30	85	85	70	53	40	35	21	12	07
35	85	85	73	57	43	38	24	15	10
40	85	85	75	60	45	41	27	18	12
45	85	85	78	63	48	43	30	21	15
50	85	85	80	65	50	45	32	23	17
75	85	85	83	75	58	53	40	32	26
100	85	85	85	80	65	60	45	37	32

The factors of Table II were applied to clock-hour figures for Mildenhall, Suffolk, for the period 1949-66 and to figures for Changi, Singapore Island, period 1958-61 plus 1964, and Freetown, Sierra Leone, period 1944-47. Table III presents the results and compares them with durations obtained directly from clock-hour data.

In the absence of adequate short-period measurements of rainfall rate it is not possible to check directly on the estimates presented in Table III, but in the case of Changi separate estimates had been made for the year 1961 using autographic records and a model shower profile as described by Briggs.³ Table III shows that for the high-intensity rainfall the two estimates for 1961 were in very good agreement and so supports the reliability of both methods of making these estimates. Table III also clearly shows how the direct analysis of clock-hour data can underestimate the probability of occurrence of high-intensity rainfall.

TABLE III—DURATION OF RAINFALL INTENSITIES EQUALLING OR EXCEEDING SPECIFIED VALUES

Place and period of data	Method of obtaining duration	Intensity (mm/h)							
		1	5	10	20	25	50	75	100
<i>hours per year</i>									
Mildenhall (1949-66)	(a) Directly from clock-hour data	124	9.9	1.1	0.2	0.1	0	0	0
	(b) Using estimated two-minute rainfall rates	206	33.1	8.2	1.3	0.8	0.12	0.03	0.01
Changi (1958-61) plus 1964)	(a) Directly from clock-hour data	241	100	56	22	16	1.9	0.3	0.1
	(b) Using estimated two-minute rainfall rates	208	79	44	21	16	6	2.5	1.3
	(c) Using estimated two-minute rainfall rates (1961 only)	—	—	36	—	13	5	—	1.3
	(d) Estimates for 1961 using autographic records and assumed shower profile ³	—	—	46	—	15	5	—	1.1
Freetown (1944-47)	(a) Directly from clock-hour data	445	187	99	35	25	4.1	1.0	0.3
	(b) Using estimated two-minute rainfall rates	380	137	81	39	29	11	4.9	2.8

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551.577.36:551.591.36(261+4)

DISTRIBUTION OF PRECIPITATION AND THE VARIATION OF VISIBILITY IN PRECIPITATION

By W. D. SUMMERSBY

Summary. In this investigation the area considered extends from the eastern and northern extremities of the Baltic across the British Isles to include the ocean weather stations (OWS) 'I' and 'J'. A selection of observations for 13 stations spanning this region are examined to show how precipitation varies in type and intensity across it and, using the observations nearest midday, how visibility varies in precipitation. Interest is mainly confined to coastal and sea areas rather than to inland stations.

Distribution of precipitation. In describing the weather of a region it is relevant to state what forms of precipitation occur, how frequently they occur at various places within the region, and how these frequencies compare with one another, both from place to place, and from one type of precipitation to another. Figure 1 shows the region considered, extending from Leningrad in the east and Lulea-Kallax near the northern end of the Gulf of Bothnia, across the North Sea and the British Isles to include OWS 'I' and 'J' in the west; it also shows the positions of the 13 stations from which data were taken.

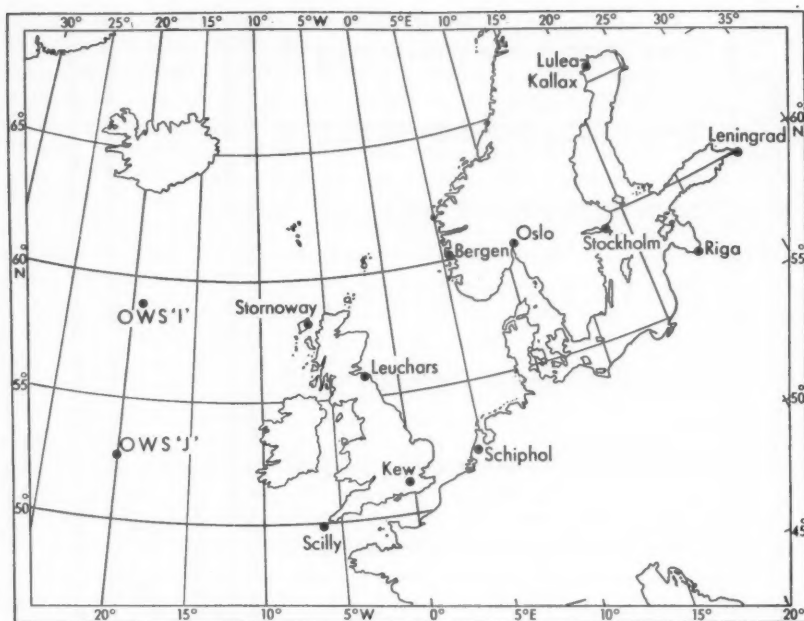


FIGURE 1—MAP SHOWING POSITION OF OBSERVING STATIONS

The approximate percentage of observations having precipitation of various types and intensity and of no precipitation is shown in Table I. Account is taken of the fact that the present-weather code has changed over the years and that sometimes the definition of a present-weather code figure includes more than one form of precipitation. While a homogeneous selection of years and times of day would have been preferable, the restricted published data available made it necessary to use the various times and periods quoted in Table I. Use of a longer, or a different but equally short, period would bring slightly different results, but as far as is known the periods selected were not abnormal. Just under 3000 observations were considered for each station, though for the region as a whole the proportion of daylight observations exceeds that of observations made at night.

Nearly all forms of precipitation occur from time to time throughout the region, but their relative frequencies both compared with one another and from place to place vary considerably. For example, the frequency with which precipitation falls as rain over the open sea (see OWS 'I' and 'J') far outstrips that of any other form. Only at Leningrad and Lulea-Kallax does the total of the rain and drizzle frequencies not exceed that of the sleet* and snow. The figures of Table I summarize the frequencies for a whole year, and in deriving them monthly and seasonal frequencies became available. It

* In the United Kingdom the term sleet is used to denote precipitation of snow and rain (or drizzle) together or of snow melting as it falls, but it has no agreed international meaning.

TABLE I.—PERCENTAGE FREQUENCY OF OCCASIONS OF DIFFERENT TYPES OF PRECIPITATION OR OF NO PRECIPITATION

Precipitation Type	Intensity	Leningrad	Riga	Oslo	Bergen	Lulea-Kallax	Stockholm	Schiphol	Scilly	Stornoway	Leuchars	Kew	OWS 'I'	OWS 'J'
Drizzle	Slight	1.1	1.2	1.3	0.7	1.1	1.5	1.9	2.2	3.0	1.9	1.6	2.8	3.7
	Moderate	0.4	X	0	0.3	0.1	0	0	0.4	0	0.1	0.3	0.2	0.2
	Heavy		0	0	0.1	0	0	0	X	0	X	X	0	X
Rain	Total	1.5	1.2	1.3	2.1	1.2	1.5	1.9	2.6	3.1	2.0	1.9	3.0	3.9
	Slight	3.6	3.4	4.9	7.6	3.5	4.4	6.7	4.7	6.3	6.5	6.5	8.6	8.3
	Moderate	1.6	0.2	1.1	2.4	0.6	0.4	0.6	3.2	2.7	1.6	2.0	1.1	1.4
	Heavy	0.1	0	0	0	0	0	0	0.1	0.5	0.5	0.1	0.1	0.1
	Sit shower	0	0	1.5	3.2	0.7	1.5	3.1	0.1	1.1	1.1	0.6	0.7	0.3
Snow	Mod/hvy shower	0.1	0.4	0.2	1.4	0.2	0.3	0.2	0.4	0.7	0.2	0.5	0.7	0.3
	Total	5.4	5.2	7.7	14.7	5.0	6.6	10.6	8.7	13.3	10.1	9.7	15.2	13.6
Sleet*	Slight	0	0	0.8	0.5	0.6	0.6	0.1	0	X	0.1	0.1	0.1	0
	Mod/hvy	X	X	0.2	0.1	0	0.1	0	0	X	0.2	0.1	0	0
	Sit shower	0	0	X	0.4	X	0.1	0	X	0.1	X	0	0.1	X
Snow	Mod/hvy shower	0	0	X	0.2	0	0	0	0	0.1	0	0	X	X
	Total	X	X	1.1	1.2	0.6	0.8	0.1	X	0.3	0.3	0.2	0.2	0.1
	Slight	6.7	2.7	5.9	1.2	7.8	4.2	0.4	X	X	0.2	0.2	0.1	0
	Moderate	2.9	0.9	0.9	0.4	2.2	0.9	0.1	0	X	0.1	0	X	0
	Heavy	0.3	0.2	0	0	0.1	0.2	0	0	0	0	0	0	0
Hail	Sit shower	0	0	0.2	0.9	0.1	0.8	X	0	0.2	0.3	0.1	0.3	0
	Mod/hvy shower	0.1	0.1	0	0.2	0	0.4	0	X	0.1	0.1	X	0.2	0
	Total	10.0	3.9	7.0	2.7	10.2	6.5	0.5	0.1	0.4	0.7	0.3	0.6	0
No precipitation (all types) and hail	Slight	X	0.1	0	X	0	0	0	0.1	X	0	0	0.2	0.1
	Total showers	83.0	89.5	82.9	79.3	83.0	84.6	86.9	88.6	83.0	86.9	87.9	80.9	82.4
	Total	0.2	0.6	1.9	6.3	1.0	3.1	3.3	0.8	4.3	1.9	1.2	6.2	3.9

*In the United Kingdom the term sleet is used to denote precipitation of snow and rain (or drizzle) together, or of snow melting as it falls, but it has no agreed international meaning. Note: Values less than 0.005 per cent are shown as 0 and values from 0.005 to less than 0.05 per cent as X. Where necessary slight moderate and heavy have been abbreviated to 'sl, mod and hvy'. Several values of X totalling 0.05 per cent or more are allowed for in the column totals.

Notes on data and sources: Leningrad—Russian daily weather reports 1936–37 at 0100, 0700, 1300 and 1900 GMT daily.

Riga — North German weather reports and charts 1942–43 at 0200, 0800, 1400 and 1900 GMT daily.

Stockholm, Oslo, Bergen and Lulea-Kallax — U.S.A. synoptic weather maps — Part II 1956–62 at 1200 GMT daily.

Schiphol — Synoptic and upper air observations in the Netherlands 1960–61 at 0000, 0600, 1200 and 1800 GMT daily.

Scilly, Stornoway, Leuchars, Kew, OWS 'I' and 'J' — Manuscript data held in the Meteorological Office 1957–60 at 0000, 0600, 1200 and 1800 GMT daily, but Kew limited to 0600, 1200 and 1800 GMT daily.

Details of observing stations: Bergen — Fredrikberg, 60°24'N, 5°19'E, 144 ft above MSL to 1956 and Fietland 60°17'N, 5°14'E, 164 ft above MSL from 1 Jan 1957. Lulea-Kallax 65°33'N, 22°08'E, 52 ft above MSL.

became evident that while the liquid forms of precipitation are the most frequent over most of the region, snow is normal in winter within the area of continental climate. Table I also shows that at sea the frequency of drizzle is about one third that of rain (excluding showers), and the frequency of slight showers is slightly greater than that of drizzle of all intensities (OWS 'I' and 'J' together). These proportions remain substantially unchanged along the western seaboard of the British Isles, but in the only slightly more sheltered situation at Bergen there are only about one fifth as many occasions of drizzle as of rain (even excluding showers), though the total percentage frequency of rain combined with that of drizzle remains little less than at the ocean weather stations.

The whole region has snow from time to time, though infrequently in the south-west. Reporting errors arise during snow because in periods of drifting it is almost impossible to say if more snow is falling or not. Table I also shows that sleet is of greater frequency in the north than in the south and that it is relatively infrequent both in the coldest and in the warmest parts of the region. For example, OWS 'I' has a frequency of all intensities of sleet of 0.2 per cent, while OWS 'J' has only 0.1 per cent and this is limited to showers. Leningrad and Riga both with less than 0.05 per cent (none in the form of showers) are outstanding in the east. Distinctly more sleet is reported from places intermediate between the coldest and warmest parts.

Rain falling from shower cloud is often more intense than continuous rain, and Table I shows more slight rain showers at OWS 'I' and 'J' than at any of the land stations, though Bergen, Schiphol and Stornoway, all having maritime climates, are not much less affected. The Table also shows that, at sea, about one quarter of the occasions of precipitation reported are showers (OWS 'I' and 'J' together), and that OWS 'I' has nearly twice as many showers as OWS 'J', whereas in the east (Leningrad and Riga together) the proportion of occasions with showers is much less (about 1/34). Seasonally there is a summer maximum on the continent, and Summersby¹ has shown that there is a winter maximum at sea for all types of showers combined. The geographical position of Bergen gives it the highest frequency of showers (all types) in Table I, probably because the showers are caused by instability in maritime air, by orographic action nearby and by convection over land heated by day in summer.

When convective activity is vigorous and deep, hail may form within cumulonimbus cloud and may reach the ground. No clear geographical distribution emerges beyond the greater frequency of hail at sea and at stations well exposed to maritime influences. Bilham² gives the hail frequency inland in Britain as varying from about 3 to 25 occasions per year, there being no obvious association with high ground. In winter, low temperature and moisture content successfully inhibit hail in the east of the region, though during the summer hail forms over the continent more often than over the ocean. Table I shows less frequent hail at OWS 'J' than at OWS 'I', and this is a reflection of the greater frequency with which deep cold air overruns the north-west of the region.

Visibility in precipitation. The forecasting of visibility in precipitation presents some difficulty because the degree of obscurity found is fairly varied for a given intensity of precipitation. Analyses of the distribution of visibilities

in precipitation of varying types and intensities have been produced by Jefferson³ for a region well to the north of Britain and by Ross⁴ for Kinloss. The present analysis is of interest in that it covers an area further south than the earlier ones and extends considerably on each side of the line usually taken as dividing oceanic from continental climates. The general agreement between this and the earlier analyses is reassuring.

Wright,⁵ Poljakova,⁶ and Poljakova and Tret'jakov⁷ have attempted calculations of the obscurity to be expected from precipitation in which the concentration of scattering particles is known and the drop sizes are also known. Such attempts give only rough estimates, because it always has to be assumed that the precipitation intensity and drop-size spectrum as measured at a point is constant throughout the area spanned when measuring the visibility. A fair spread of visibility values should be expected in precipitation of a given intensity when it is remembered that the given intensity can occur with a large number of small drops, or a small number of large drops or a mixture of the two. The drop-size spectrum may or may not distinguish rain from drizzle, but for calculation of visibility this is immaterial. Richards's⁸ work in Canada, though directed at assessing the expected accretion of snow from the visibility reported during its deposition, shows a good deal of scatter in the visibilities reported for given rates of accretion. Particle size plays a part in determining visibility, in that visibility on occasions of equal concentration of particles is more restricted when the particles are large than when they are small. Snowflakes are much larger than the raindrops they form on melting, so that the physical state of the precipitation also plays a large part in determining visibility. Thus, for a given water content of precipitation, visibility in snow is likely to be less than in other forms of precipitation.

Reference to the footnote of Table I shows that observations at about midday were the only ones common to all 13 stations used. Therefore the second part of this descriptive work used only the observations nearest to midday. Snow and sleet were considered together. It was found that for the more intense forms of precipitation, there were insufficient occasions at individual stations to obtain a representative distribution of visibility. Table II therefore gives the percentage distribution of visibility code figures for the general weather headings: no precipitation, drizzle, rain, snow and sleet, and showers of all types, all being irrespective of intensity. Those few occasions when more than one type of precipitation is included by a single present-weather code figure were equally shared between the types of precipitation involved. For these reasons it is not possible to calculate percentages of occurrence in Table I from the various parts of Table II.

The largest percentage for each line of Table II is printed in bold type: a general reduction can be seen in visibility in precipitation compared with that in no precipitation. Scandinavian places stand out as a group where visibility without precipitation was particularly good, and Leningrad, Schiphol and Kew are places clearly affected by industrial and domestic pollution. It is possible that at some stations difficulty arises when reporting visibility because of the lack of good visibility points at great distances. This difficulty is most marked at the ocean weather stations where the horizon is about 11 km distant, though there is good agreement between OWS 'I', OWS 'J' and Stornoway.

TABLE II—PERCENTAGE FREQUENCY OF VISIBILITY CODE FIGURES AT ABOUT MIDDAY IN VARIOUS TYPES OF PRECIPITATION AND IN NO PRECIPITATION

Type of pptn	Station	Visibility code figure										Number of cases
		0	1	2	3	4	5	6	7	8	9	
		<50 m	50-200 m	200-500 m	500-1000 m	1-2 km	2-4 km	4-10 km	10-20 km	20-50 km	>50 km	
No pptn	Leningrad	0	X	X	1	1	5	40	52	1	X	523
	Riga	X	1	1	1	1	4	12	20	37	23	573
	Oslo	0	X	1	X	1	3	6	10	34	45	2044
	Bergen	X	X	X	X	X	X	4	8	39	49	1980
	Lulea-Kallax	0	X	X	1	X	1	6	6	20	66	2070
	Stockholm	0	0	X	X	1	1	6	12	30	50	2112
	Schiphol	X	X	X	X	2	8	26	30	33	1	627
	Scilly	X	X	1	1	X	2	22	25	47	2	1303
	Stornoway	0	0	X	X	2	1	5	21	63	10	1188
	Leuchars	0	X	X	1	2	4	14	23	47	9	1264
	Kew	X	X	1	1	5	7	25	25	32	4	1270
	OWS 'I'	0	0	X	X	X	1	4	19	67	9	1055
	OWS 'J'	0	X	X	1	1	2	5	20	63	8	1106
Drizzle	Leningrad	0	0	0	6	18	6	70	0	0	0	17
	Riga	0	0	0	0	18	9	37	18	0	9	11
	Oslo	0	0	9	4	18	30	18	13	4	4	46
	Bergen	0	0	0	2	5	18	58	15	1	1	87
	Lulea-Kallax	0	0	0	5	19	16	25	14	16	5	37
	Stockholm	0	0	0	0	9	25	39	23	4	0	56
	Schiphol	0	0	6	13	6	31	38	6	0	0	16
	Scilly	0	0	0	10	32	27	31	0	0	0	41
	Stornoway	0	0	0	0	2	11	62	21	4	0	57
	Leuchars	0	0	3	3	6	25	35	22	6	0	36
	Kew	0	0	0	7	18	14	46	11	4	0	28
	OWS 'I'	0	0	0	2	6	27	40	19	4	2	48
	OWS 'J'	0	0	0	0	10	26	47	10	6	1	70
Rain	Leningrad	0	0	0	0	5	24	58	13	0	0	38
	Riga	0	0	0	0	18	11	29	28	14	0	28
	Oslo	0	0	1	2	5	18	38	21	11	4	179
	Bergen	0	0	0	0	1	5	29	32	30	3	275
	Lulea-Kallax	0	0	0	0	4	8	30	18	28	12	121
	Stockholm	0	0	1	1	5	10	30	29	20	4	138
	Schiphol	0	0	0	0	2	13	57	26	2	0	47
	Scilly	0	0	1	3	5	13	49	22	7	0	103
	Stornoway	0	0	0	0	2	2	39	45	12	0	121
	Leuchars	0	0	0	2	2	16	40	31	8	1	127
	Kew	0	0	0	2	16	16	41	20	5	0	128
	OWS 'I'	0	0	1	1	2	9	33	40	14	0	128
	OWS 'J'	0	0	0	1	2	5	28	45	17	2	110
Snow or sleet	Leningrad	0	1	4	5	14	33	40	3	0	0	79
	Riga	0	0	0	15	32	17	24	6	6	0	34
	Oslo	0	0	0	4	19	32	30	11	4	0	169
	Bergen	0	0	0	10	10	17	34	19	10	0	41
	Lulea-Kallax	0	0	0	3	16	28	33	8	11	1	253
	Stockholm	0	0	0	4	15	14	43	13	11	0	131
Showers (all types)	Schiphol	0	0	0	0	17	33	50	0	0	0	6
	Leningrad	0	0	0	0	0	4	48	44	4	0	25
	Riga	0	3	0	3	3	19	22	41	6	6	32
	Oslo	0	0	0	0	0	5	18	21	33	23	62
	Bergen	0	0	0	1	1	3	20	30	40	5	166
	Lulea-Kallax	0	0	0	0	0	0	16	40	44	25	25
	Stockholm	0	0	0	1	1	11	19	30	27	11	75
	Schiphol	0	0	0	0	0	30	37	33	0	33	33
	Scilly	0	0	0	0	8	0	46	15	31	0	13
	Stornoway	0	0	0	1	3	2	13	48	33	0	91
	Leuchars	0	0	6	0	10	0	26	39	19	0	31
	Kew	0	0	0	0	3	3	28	17	49	0	29
	OWS 'I'	0	0	1	0	0	2	13	35	49	0	84
	OWS 'J'	0	0	0	0	0	6	22	35	37	0	54

X = <0.5 per cent. The values quoted are correct to the nearest one per cent. Bold figures represent the largest percentage for each station.

When it was drizzling, most stations (11 out of 13), reported visibility in the range of code figure 6 (4-10 km) more often than in the range of other code figures. Oslo (Gardemoen) differs from many other places in that it is higher above sea level, while at Scilly visibilities were rather worse than at any of the other stations.

In rain, as well as in drizzle, most places (9 out of 13) reported visibility code figure 6 more often than other code figures. However, those places not reporting this code figure most frequently, reported code figure 7 (10–20 km), whereas in drizzle, those places not reporting code figure 6, most frequently gave code figures 4 (1–2 km) or 5 (2–4 km). It is probably significant that the places having code figure 7 as the most frequent in rain are all well removed from sources of pollution and include OWS 'I' and 'J'. Except for OWS 'J' they also lie in the northern parts of the region, where polar and arctic air are commoner.

Stations in the central and western parts had insufficient snow at midday for the percentage distributions here calculated to be representative, and are therefore omitted from Table II if they had five occasions or less of snow and sleet. The infrequency of snow in these parts is commented upon in discussing Table I. The more north-easterly stations had distributions of visibility code figures in snow rather similar to those in drizzle, visibility tending to be slightly worse than in rain.

Showers mostly occur in polar and arctic air masses, in which visibilities are otherwise normally good over the region. The limited horizontal extent of showers enables objects at a distance to be viewed partly through precipitation and partly through clear air. The visibilities reported in showers are therefore not so much reduced as they would be were the precipitation more widespread and continuous, and of the same intensity as often occurs in showers. The distribution of the most frequently occurring visibility code figures is rather more scattered than in other forms of precipitation, lying in the range code figures 6–9 inclusive, but code figures 7 and 8 (covering 10–50 km) were those most frequently occurring across the region as a whole.

Since reasonable consistency was found from station to station, percentage frequencies of reported visibility code figures in varying intensities of precipitation were combined for the 13 stations regarded as representative of the region as a whole, and Table III gives the results. The maximum percentage in each intensity and type of precipitation is marked with an asterisk. In addition Table III shows in bold figures the three consecutive visibility code figures which together have the biggest combined percentage.

TABLE III—PERCENTAGE FREQUENCY OF VISIBILITY CODE FIGURES REPORTED IN PRECIPITATION OF DIFFERENT INTENSITIES, AND IN NO PRECIPITATION

Visibility code figure	No precipitation	Drizzle			Rain			Snow/sleet			Showers (all types)	
		A	B	C	A	B	C	A	B	C	A	B/C
0	X	0	0	0	0	0	0	0	0	0	0	0
1	X	X	0	0	0	0	0	X	1	0	X	0
2	1	1	0	0	X	X	0	0	2	8	0	2
3	1	3	2	8	1	1	4	1	14	54*	0	2
4	1	9	23	46*	4	7	8	11	40*	15	1	5
5	2	20	36	8	8	19	29	25	31	15	2	9
6	11	45*	37*	38	32	50*	46*	40*	10	8	17	31*
7	17	16	0	0	33*	17	13	12	1	0	32	30
8	38*	5	0	0	19	6	0	10	1	0	40*	20
9	29	1	2	0	3	0	0	1	0	0	8	1
No. of cases		17 115	481	56	13	1218	301	24	570	145	13	555 165

A = slight, B = moderate and C = heavy. X = <0.5 per cent. The three consecutive code figures which give the biggest combined percentage have their percentages printed in bold and the maximum is marked with an asterisk. The whole region is represented by 13 stations and the values quoted are correct to the nearest one per cent.

A general tendency for visibility to decrease with increasing intensity may be seen, the least effect on visibility occurring in showers and the most in snow or sleet. It should be appreciated that the divisions between slight and moderate, and moderate and heavy precipitation occur when the rates of accretion in recording rain-gauges reach critical values of 0.5 mm per hour and 4.0 mm per hour respectively. At stations, including the ocean weather stations, that are not equipped with such gauges, the decision whether precipitation is slight, moderate or heavy is subjective, and errors stemming from this are impossible to eliminate. However, reasonable consistency is found and these results are in general agreement with similar investigations in the past.^{3,4}

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NOTES AND NEWS

Cloud physics research in Czechoslovakia

Dr J. Podzimek, the Director of the Institute for Atmospheric Physics of the Czechoslovak National Academy of Sciences, who was visiting England as the guest of the Royal Society, led a colloquium at the Meteorological Office Headquarters at Bracknell on 20 March. The subject chosen was the current programme of cloud physics research in his department. The main laboratories employ a staff of 22 and, in addition, the department runs a mountain research laboratory equipped with a 3.2-cm weather radar, and hopes to make use of a field observatory with a tower 80 metres high, instrumented for electric-field measurements. For three years the 21 stations throughout Czechoslovakia have made atmospheric-chemistry observations with a frequency greater than that of the rest of the European network.

Much of the research programme has been in the field of air pollution. Routine observations of the concentrations of large numbers of contaminants, made both from the surface and from aircraft, show that the atmosphere is very highly contaminated, particularly in the industrial regions. The average sulphate content in rain-water is approximately 10 times greater than the average of 6 mg/l in the non-industrial areas of Britain, and the maximum values found are considerably in excess of any measured regularly in Britain. The size spectrum of sulphate and chloride particles has also been measured, the number n with radius r being found to obey the law $n = Ar^2 \exp - (Br)$ where the constants A and B depend on the origins of the air mass. As regards the production of aerosols, the department has been studying various types of burners with particular reference to the production, on the ground, of silver iodide aerosols for cloud seeding.

A number of theoretical and experimental studies have been made of the growth of cloud particles in mixed clouds (containing both water and ice) of the stratiform type. A mathematical model of such a cloud has been set up, and the growth rates of both drops and various-shaped ice crystals calculated. This involved the use of electrical analogues in order to solve the equations of sublimation on non-spherical particles. Ice crystals grow by sublimation by the transfer of molecules from the vapour to steps on the crystal faces. These steps advance across the crystal, the rate of growth of the crystal being determined by the rate of advance of these steps. The growth by the advance of steps on the base plane of ice crystals has been calculated and the results found to differ from those of other workers in that there was no peak in the growth rate at a temperature of -11°C . In an attempt to see how the airflow around a falling particle would affect its growth, exact solutions of the Navier-Stokes equation have been found for the flow around a cylinder.

The motion of ice crystals of various shapes falling through the air, and the way in which they cluster together, has been investigated in model experiments using high-speed photography. Some work has also been started on the separation of electric charge by the thermo-electric effect in ice, both pure and doped with atmospheric contaminants.

The discussion following this talk, which was enjoyed by all those present, was concerned mainly with the possible origins of the atmospheric contaminants, many of which are still uncertain. Dr Podzimek answered several questions on this subject and also on some details of the cloud model which he was using in his calculations. As chairman of the colloquium, Dr Mason, the Director-General of the Meteorological Office, thanked Dr Podzimek for his very stimulating account of cloud physics in Czechoslovakia.

P. R. JONAS

REVIEWS

The measurement of environmental factors in terrestrial ecology, British Ecological Society Symposium Number Eight, edited by R. M. Wadsworth. 220 mm \times 140 mm, pp. x + 314, illus., Blackwell Scientific Publications, 5 Alfred Street, Oxford, 1968. Price: 55s.

The increasing application to biological field work of instruments and techniques developed largely by physicists and engineers, induced the British Ecological Society to devote a Symposium (held at the University of Reading in March 1967) to the problems involved. The published record consists of 21 papers (pp. 1-254), a valuable 37 pages describing the extensive display of working equipment on show to participants, with the addresses of manufacturers, personal details of the 400 or so attending, a subject index and one of all authors whose names are quoted anywhere in the text.

A deliberate aim was to concentrate as much upon exactly what is to be measured, as upon how the objectives may be reached. Whilst these twin aims were explicit in all contributions, the papers may be conveniently divided into: ten on mainly instrumental topics, six with an ecological bias and five giving roughly equal weight to both aspects.

I. F. Long (pp. 1-32) and J. S. G. McCulloch (pp. 205-212) give critical reviews of some existing or reasonably developed systems. Others deal with: measuring conditions in food stores (F. L. Waterhouse and T. G. Amos pp. 34-46); the use of infra-red techniques (S. D. Smith, G. E. Peckham and P. J. Ellis pp. 83-90); radio-telemetric devices (J. Bligh and S. G. Robinson pp. 225-234); the measurement of radiant energy (G. Szeicz pp. 109-130), of CO₂ (G. E. Bowman pp. 131-140), and of soil aeration (M. H. Martin pp. 181-190). M. J. Blackwell and M. R. Blackburn (pp. 213-224) stress the need for a 'systems engineering' approach to data acquisition, recognizing that a decision on equipment and processing at any one stage from sensor to eventual computer output, depends upon and influences decisions at all other stages; ready access to a qualified technician is also necessary — advice implicitly underlined by J. K. Brookhouse (pp. 243-254) when discussing computer processing.

The first of the 'ecological' papers (A. Macfadyen pp. 59-68) examines 'climate' mainly in soils and surface litter. J. W. Sibborn (pp. 91-96) asks what should be measured, whilst L. Leyton, E. R. C. Reynolds and F. B. Thompson (pp. 97-108) examine the special difficulties of measuring rainfall-interception under trees and moorland vegetation. Two contributors (E. J. Winter pp. 147-160 and D. R. Gifford (pp. 175-180) concentrate on soil water, and M. B. Alcock, J. V. Lovett and D. Machin (pp. 191-204) examine relationships between environmental factors and pasture production. All reveal, *inter alia*, the structure of biological systems to which the physical measuring systems must be matched.

The contributors to the remaining group are D. B. Idle (pp. 47-58) on surface temperature measurements; J. M. Caborn (pp. 69-81) on the measurement of wind; P. R. Newell (pp. 141-146) on light and temperature at the surface; V. I. Stewart and W. A. Adams on soil moisture (pp. 161-174), and finally A. I. Fraser (pp. 235-242) on the forest environment.

Another reviewer would classify and would evaluate the papers differently; accordingly comparisons are invidious. However, for meteorologists first entering the biological field, the six ecological papers may be recommended as 'required reading'. Predictably as in all symposia proceedings, browsing is rewarding. The last sentence of the penultimate paragraph on p. 11 seems incorrect, and would be improved by substituting 0.5°C for 0.05°C. The sentence similarly situated on p. 99 concerning the exposure of rain-gauges, also needs some elaboration to be acceptable.

R. W. GLOYNE

Exploring the atmosphere. Second edition, by G. M. B. Dobson. 225 × 145 mm, pp. xv + 209, *illus.*, Clarendon Press, Oxford University Press, Ely House, 37 Dover St, London, W.1, 1968. Price: 42s. (paperback 21s.).

This is not yet another textbook on meteorology, but a book written with the intention of presenting a general and interesting account of the earth's atmosphere to the scientifically minded public. The author has not made the mistake of making the book too comprehensive: it is of sensible length — *circa* 200 pages — and being light in weight and well printed can be regarded as easy reading: occasionally explanation tends to be rather long but this is the fault of nature, not of Dr Dobson who has the facility of explaining processes in a clear and concise manner.

The book does not touch on the dynamics of the atmosphere, and is free of mathematics and equations: the author's aim is to describe the physical properties of the atmosphere — in the first brief chapter he gives a general picture of the atmosphere, its temperature, ionization and composition. The next two chapters are concerned mainly with the temperature of the atmosphere from the surface up to great heights, with solar and atmospheric radiation, and with methods of measurement.

In the fourth and fifth chapters the reader is brought again to ground level to learn about familiar matters such as cloud, rain and thunderstorms. Chapter six deals with atmospheric ozone, a subject in which Dr Dobson has played a major role though, with characteristic modesty, his name is not mentioned. A little more might have been said about the importance of ozone in controlling the temperature and circulation of the upper stratosphere.

The atmosphere so far described has been neutral — but above the stratosphere we enter the region of the atmosphere where our main interest is in its state of excitation and ionization and for which an understanding of solar activity and sunspots, which are described in a short chapter seven, is necessary. The last four chapters give a clear description of the ionosphere, aurora, airglow, the magnetosphere and the methods by which these high levels of the atmosphere are studied.

The author has adopted the familiar lecture-room style of 'we will now . . .', but in reading the book one feels that Dr Dobson is taking only the reader himself on his journey of exploration through the atmosphere from the ground to its outer limits. Though it flags somewhat in the middle chapters, the enthusiasm of the author for everything they meet on their travels must affect all but the duller of readers. Though there are no photographs, the numerous excellent diagrams help to explain various methods and results discussed in the text. The author has not wasted time on historical reviews, but has kept in mind his single purpose of providing a contemporary description of the atmosphere, and in this he has been eminently successful. This is a sensible and readable book, and should be on the shelves of school and county libraries, and will be well read.

R. A. HAMILTON

Statistics in the computer age, by J. M. Craddock. 195 mm × 126 mm, pp.x + 214, illus., English Universities Press Ltd, London, 1968. Price: 35s. (paperback 22s.).

This book has been written with two objectives in mind. The first is to give the general reader of appreciable mathematical attainment an account of current methods of drawing conclusions from statistics with special reference to the revolution brought about by the advent of the electronic computer with its ability to do arithmetic on a scale previously inconceivable so that the statistician can, if he wishes, 'correlate everything with everything'. The second is to encourage professional statisticians to use the computer and to give them guidance in doing so.

The author covers a large field in his fifteen chapters from fundamentals in the theory of probability to the analysis of time-series. The basic ideas, mathematical parameters and frequency distributions used in statistics, are defined and described from histogram, mean, and percentile to the normal distribution, chi-square, Student's 't', Snedecor's 'F' and Sherman's 'ω'. Mode is an elementary term which is not mentioned.

The generation of random numbers and their use in determining values of statistical parameters applicable to random distributions for subsequent comparison with values computed from observations in statistical inference work are given prominence.

A particularly strong feature of the book is the account of ways in which a statistical parameter such as a correlation coefficient or chi-square can be used to test a hypothesis. The meaning of significance levels and the problems of the use of samples in this work are described in detail.

In a chapter on statistics and the electronic computers, the author gives advice out of his long experience to the statistician new to the use of these machines as well as giving much information to the general reader on methods of input and output and programming.

The analysis of time-series is one of the author's major professional interests, so it is given particularly full consideration. It starts with an account of the ways in which time-series can be generated, and the correspondingly appropriate methods of analysis for purposes of prediction of the future course of those which can be supposed to be of a stationary type. The prediction of the course of non-stationary time-series, to which class most important meteorological ones are stated to belong, is still a matter for the future. The account covers the construction of appropriate trigonometric multiplying functions — 'filters' — for the amplification of the amplitude of oscillations of specific frequencies and their application to the construction of the power spectrum of the time-series. This is probably the simplest available introduction to the power spectrum concept.

This is not an impersonal textbook. It is based on the author's personal experience and written with some fervour in areas about which the author has strong views he wishes to bring home to his readers.

The examples are naturally meteorological from the author's own work. Chi-square, for example, is used to test for a connection between the five-day temperature means of mid-August and mid-September.

No first edition is free from error, obscurity, or misprint. The contingency table of the mean monthly temperatures of February and March for central England contains two incomplete cells and one cell has an error; a more thorough explanation of this table could usefully have been given. A quantity θ_n appears without explanation on page 168. There are some slips in indices and suffixes in the mathematical formulae. A table of symbols and their meanings could usefully be added. The index is adequate.

G. A. BULL

AWARD

We note with pleasure that the International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded for this year to Professor Erik Herbert Palmén (Finland) by the Executive Committee of the World Meteorological Organization during its 21st session.

CORRECTIONS

Meteorological Magazine, May 1969, p. 148.

For Figure 2 please see correct Figure 2 below.

P. 149 line 3 'For increase' read 'decrease'.

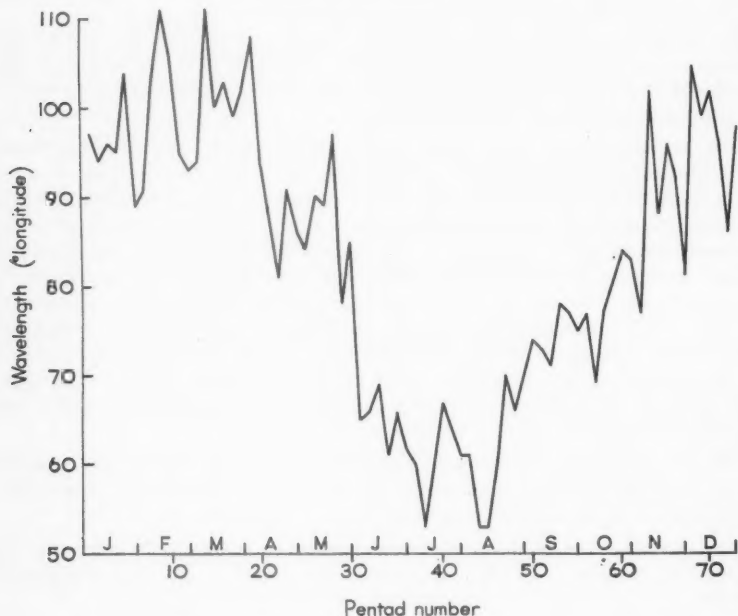


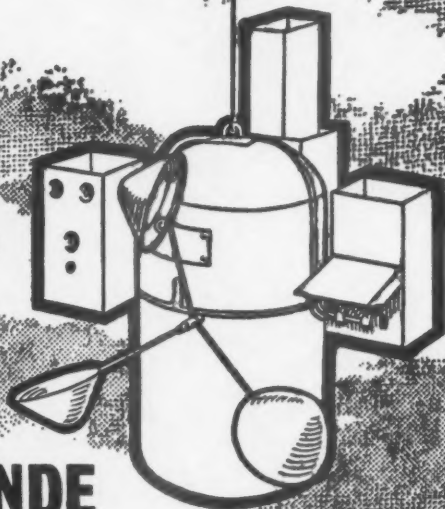
FIGURE 2—AVERAGE WAVELENGTH ACROSS ASIAN RIDGE (500 mb) AT 50°N.
PERIOD 1949-64

Meteorological Magazine, July 1969, Plate III, title, lines 4 and 6.

For 'illuminator' read 'illuminometer'.

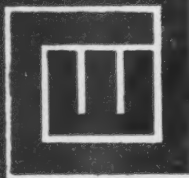


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